

## **Wave-Current Interaction in Coastal Inlets and River Mouths**

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### **LONG-TERM GOALS**

The wave-driven dynamics of coastal areas are important for circulation and mixing, transport processes, and accessibility by vessels. The long-term goal of this study is to improve our understanding, observational capability, and model representation of wave-current interaction in complex coastal inlets, and determine the role of nonlinearity and inhomogeneity on wave statistics in such areas.

### **OBJECTIVES**

The specific objectives of this study are to: 1) develop observational capability using wave- and current- resolving Lagrangian drifters to study wave-current interaction, and contribute to a comprehensive community data set of coastal inlet and river mouth processes, 2) better understand the role of current shear and wave inhomogeneity and nonlinearity in wave-current interaction through analysis of observations and modeling, and 3) develop predictive modeling capability of wave statistics in a complex coastal environment with two-dimensional bathymetry and currents.

### **APPROACH**

To better understand interactions between waves, currents and topography in a coastal inlet, and improve predictive capabilities, we propose an integrated study that combines field observations acquired using newly developed drifter buoys, with advances in theory and numerical modeling of wave-current interaction, random wave focusing and wave dissipation.

### **WORK COMPLETED**

We have continued the development of Lagrangian drifter buoys that can resolve both surface currents and waves. To augment the GPS observations (sampled at 1Hz), which do not resolve the

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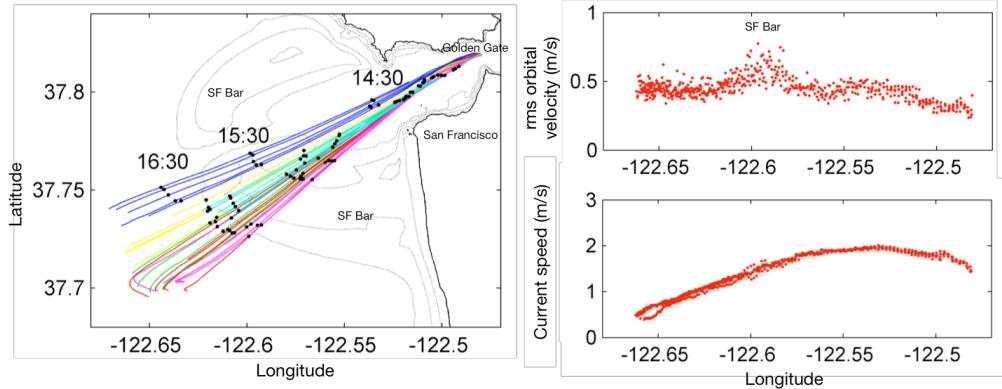
vertical motions as accurate as they do the horizontal, the new Wave-Resolving-Drifter (WRD) drifter buoys are equipped with off-the-shelf accelerometer packages. These sensors are capable of resolving higher frequencies (10 Hz sampling rate) that are of interest to characterize the wind-wave spectrum, and provide the resolution of the vertical motions that is lacking in the GPS sensor observations.



*Figure 1 Left panel: Breaking waves as seen from R/V Questuary over the sill in Raccoon Strait (San Francisco Bay) opposing a developing flood tide. Right panel: drifter deployment in San Francisco Bight (camera is looking north-westward from under the Golden Gate).*

We conducted several experiments in Raccoon Strait located inside San Francisco Bay to test instruments and collect a comprehensive dataset of wave-current interaction in this area using both free-floating (Lagrangian) and bottom-mounted (Eulerian) instruments (see figure 1, left panel). We also conducted experiments in the San Francisco Bight (see figure 1, right panel), between the Golden Gate and the San Francisco Bar (see figure 2). The Bight experiments are aimed at testing the new Wave-Resolving Drifters (WRDs) in more energetic wave- and current conditions on larger scales in a natural coastal inlet. All these experiments were single or two-day experiments during which we experimented with deployment and retrieval strategies, made observations during different phases of the tidal cycle, and collected data (currents, stratification, and waves) to better understand the current and wave regimes in the area.

To successfully determine statistics from highly non-stationary drifter time series we have experimented with cluster deployment of buoys such that statistics can be determined through ensemble averaging (see figure 2). Even in strong ebb currents, as present near the Golden Gate, the clustering of buoys showed very promising results and allows us to identify large-scale bottom features from variations in wave statistics (see right panel figure 2).



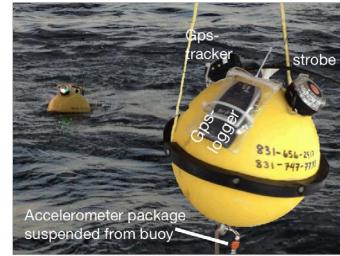
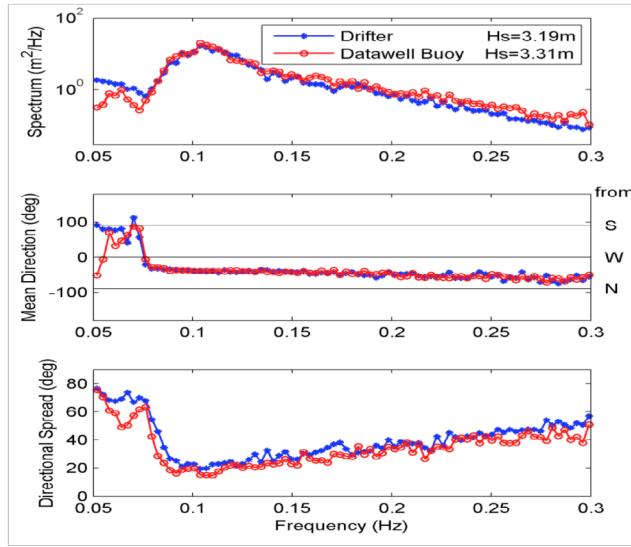
**Figure 2** Drifter observations collected during the second San Francisco Bight Experiment. Six clusters of five Wave-Resolving Drifters (WRDs) were deployed in 10-minute intervals during the peak ebb current on 27 April 2012 near the Golden Gate Bridge. Left panel shows tracks for each cluster of WRDs (track color indicates cluster) for buoys traversing the SF Bar (the 4, 8, 12 and 16 m depth contours are drawn in grey contours); small black dots indicate the drifter positions at hourly intervals. Right panels show two-minute rms horizontal wave orbital velocities (top) and two-minute mean surface currents (bottom) as recorded by the WRD cluster indicated in red (left panel).

## RESULTS

We conducted several short experiments in Raccoon Strait (May, July, and October 2011, May 2012), and the San Francisco Bight (October 2011, February and April 2012). During these experiments we deployed a large number of experimental drifter buoys, conventional Datawell buoys, and used ship- board ADCP and a CTD to capture current and stratification characteristics. We deployed two bottom- mounted ADCP instruments in Raccoon Strait to combine Lagrangian and Eulerian observations of the flow and wave dynamics. These experiments were conducted from the R/V Point Sur operated from Moss Landing Marine Laboratories, and the R/V Questuary and R/V Salty Dog, both operated from the Romberg Tiburon Center for Environmental Studies.

### Instrument validation

One of the new developments tested during the pilot experiments was the use of off-the-shelf accelerometers. These accelerometer packages accurately resolve vertical motions at high frequencies (10 Hz sampling rate) and thus complement the GPS sensors, which are most accurate for horizontal motions at lower frequencies (< 0.5 Hz).



**Figure 3 Left panels:** Comparison of spectral estimates from the new Wave-Resolving Drifter (WRD) and Datawell Directional Waverider buoy. These observations were made in energetic swell (3.3 m significant wave height) in deep water off the coast of Monterey. Spectral estimates are based on a 3 hour-38 minutes-long data record. Drifter-measured surface height spectrum (estimated from the GPS horizontal Doppler velocity data), and directional wave estimates (based on accelerometer-GPS velocity cross-spectra) are in excellent agreement with Datawell estimates. Right panels show a close-up of a WRD with instrumentation (top) and preparation of WRD array prior to deployment (bottom).

Results of a validation test where the new drifter was deployed alongside a Datawell Waverider in deep water off the central California coast are shown in Figure 3. Data were collected for about 4 hours in energetic (significant wave height 3.3 m) swell conditions. The drifter-measured surface height spectrum (estimated from the GPS horizontal Doppler velocity data) is in excellent agreement with the Datawell estimate. The accelerometer data are somewhat noisier than the GPS data at swell frequencies, but the dominant source of noise associated with the tilt of the sea surface is in quadrature with the surface height and thus does not significantly affect the directional wave measurements (based on accelerometer-GPS velocity cross-spectra), which agree well with the Datawell estimates (lower two panels of Figure 3).

### Observations of wave-current dynamics

Observations in Raccoon Strait show a combination of strong internal hydraulics in the lee of the sill that may play an important role in the surface wave dynamics. Analysis to explain the observed surface wave dynamics is ongoing.

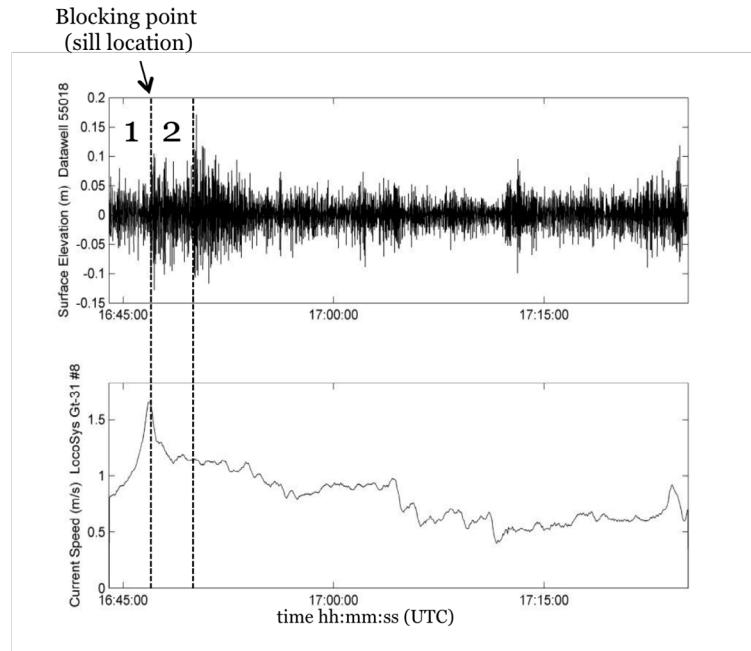
During the flood tide, surface waves may get trapped between the sill (maximum current velocity) and an outcropping front developing between the incoming ocean water and fresher surface waters

in the lee of the sill (see figure 1 for photograph of surface waves). As the flood develops, the denser ocean water plunges underneath the fresher bay water, and the flood current develops what appears an internal lee- wave behind the sill.

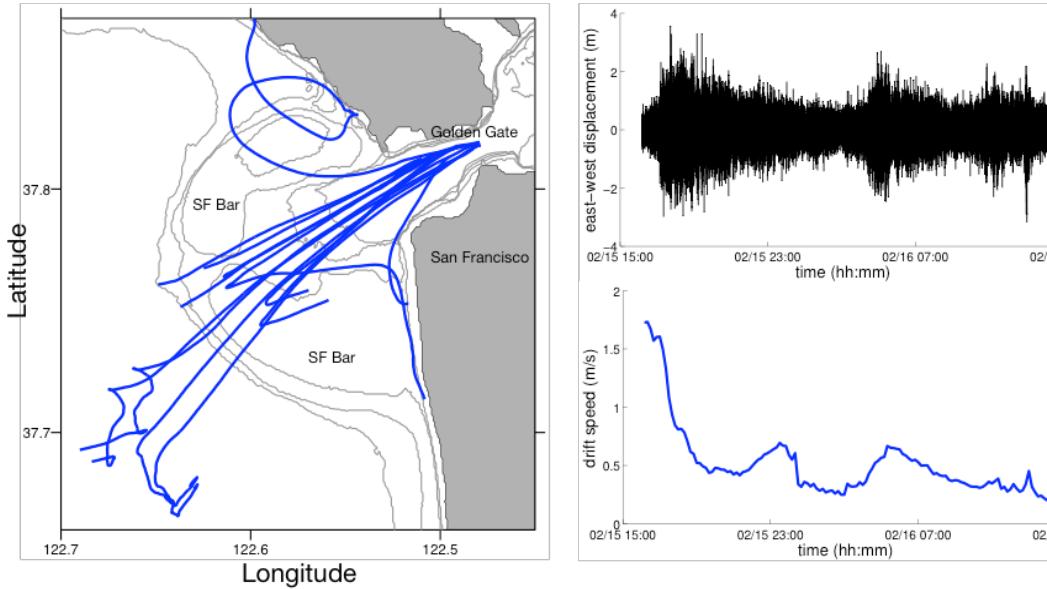
Surface wave energy is enhanced in the blocking zone (see figure 4) where the waves are relatively steep and breaking occurs. From a directional analysis (not shown), based on observations of horizontal and vertical motions, it is seen that the higher-frequency waves ( $> 0.3$  Hz) propagate in opposite direction on either side of the blocking point.

These initial observations show a complicated interaction between tidal currents, stratification, topography and surface waves, the details of which are not yet fully understood. In the following series of experiments in this area we will focus on the origin of the surface wave energy and its directional properties, and the effects of the internal hydraulics on the surface dynamics.

The observations collected in the San Francisco Bight showed that WRDs can be used in energetic conditions to study the ebb current structure, and capture regional variations in the waves (see figure 5). The drifter tracks reveal a complicated coastal current structure and large variations in wave conditions along the tracks.



**Figure 4.** Top panel: time series of surface elevation observed with Datawell buoy. Bottom panel: currents observed with GPS receiver attached to the same buoy. The time intervals marked 1 & 2 in the top panel approximately correspond to just outside (1) and just inside (2) the blocking zone.

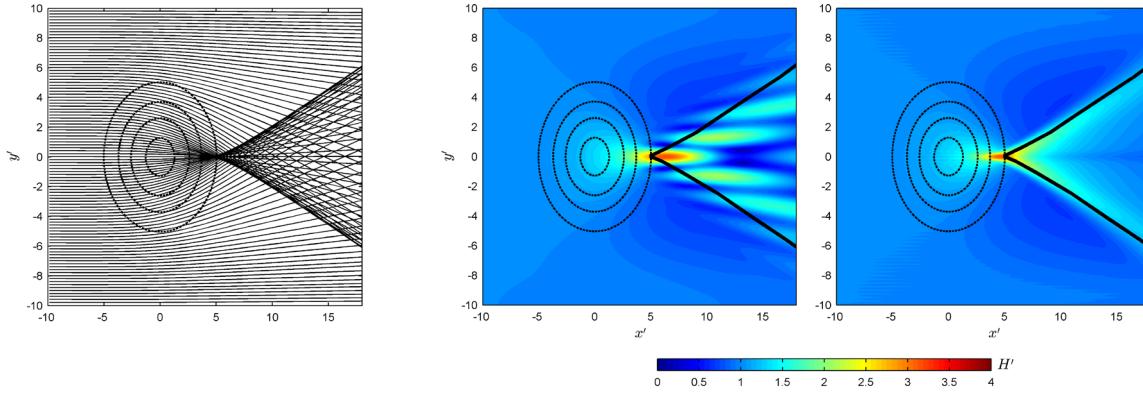


**Figure 5 Results from the San Francisco Bight experiment. On 15 February 2012, Wave- Resolving Drifters (WRDs) were deployed at the Golden Gate Bridge during ebb tide. Left panel show 14 drifter tracks (blue curves) drifting toward the San Francisco Bar (the 4, 8, 12 and 16 m depth contours are drawn in grey contours); buoys were recovered 6 to 24 hours after deployment at the bar, further offshore, and on beaches north and south of the Golden Gate. Right panels show wave-resolved east-west motion (top) and 10- minute averaged drift speed (bottom) as recorded by the WRD following the most northerly track (see left panel).**

## Model development

In areas of strong wave-current interaction, and in the presence of focusing, reflection, and blocking of waves, inhomogeneous and non-Gaussian effects are important. To improve modeling capability of such dynamics we have started development of a stochastic model that incorporates inhomogeneous effects in random waves, and can represent wave dynamics in focal zones (Smit & Janssen, 2011). The model is a natural extension of quasi-homogeneous theory (the radiative transfer equation) and can deal with inhomogeneities in wave fields of arbitrary spectral shape.

This quasi-coherent approximation resolves coherent interference contributions that are important in wave focal zones. The omission of such terms, such as implied in quasi-homogeneous theory, will result in dramatically different statistics in areas of strong inhomogeneity such as produced by interaction with current jets and coastal bathymetry (figure 6).



**Figure 6** Shown are different approximations to wave focusing over a shoal. Narrow-band waves are propagating from left to right; depth contours are shown as thin black lines. Left panel shows ray pattern of geometrical optics, with well-defined focal point and caustic region behind shoal. Middle panel shows model results with coherent stochastic model, and right panel shows the predicted energy distribution by the radiative transfer equation. It is clear that coherent patterns in spatial energy distribution in caustic area (caustic lines are approximately indicated by thick solid lines in panels b, c, and d) are not resolved in the radiative transfer equation. Such coherent structures are needed to predict wave energy variations in focal zones. Near the caustics the radiative transfer equation, on which most operational wave models are based, is highly inaccurate.

## IMPACT/APPLICATIONS

The development of inexpensive drifter buoys equipped with GPS sensors and accelerometer packages that resolve both surface waves and surface currents, will extend observational capability to areas where it is difficult to deploy and maintain moorings (such as in strong currents and/or energetic waves).

The observations of wave-current interaction in the presence of variable (tidal) currents, topography, and stratification, will contribute a comprehensive new data set that will improve our understanding of wave variability in coastal inlets and river mouths. These observations can be used to test theories and models, either existing, or those developed within the scope of this study.

The development of a stochastic wave model that resolves inhomogeneous effects in random waves, is an important and critical step to develop statistical modeling capability of wave dynamics in complex coastal environments.

## RELATED PROJECTS

The development of the GPS-tracked drifter buoys was started as part of the ONR HiRes DRI to enable deployment of a greater numbers of instruments to capture the spatial variability of waves

and currents. The instrument development and deployment strategies planned in the present project build on our findings during the HiRes DRI.

The development of a transport model for non-Gaussian and inhomogeneous wave fields also contributes to and benefits from progress in the ongoing Wave Modeling NOPP.

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